

# **Synchro-Phasor Data Conditioning and Validation Project Phase 3, Task 1**

## **Report on Lessons Learned in the DV&C Project**

Prepared for the  
Office of Electricity Delivery and Energy Reliability,  
Transmission Reliability Program of the U.S. Department of Energy  
Under Contract No.DE-AC03-76SF00098

Prepared by:



**Electric Power Group**

Ken Martin  
Jianzhong Mo

Project Manager: Dejan J. Sobajic

**September 30, 2014**

## Acknowledgement

The work described in this report was coordinated by the Consortium for Electric Reliability Technology Solutions, and funded by the Office of Electricity Delivery and Energy Reliability, Transmission Reliability Program of the U.S. Department of Energy through a contract with Electric Power Group, LLC administered by the Lawrence Berkeley National Laboratory.

## Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

## Preface

Synchrophasor systems are being deployed in power systems throughout the world. As operations and system controls become more reliant on synchrophasors, it is essential that the data is correct and accurate to prevent errors in operation. Data needs to be validated to assure no errors have been introduced in communication and processing. It also needs to be conditioned with other comparisons to assure it is accurate. Validation and conditioning must be accessible to applications using the data so they can make decisions in real-time to operation. The Department of Energy (DoE) has funded this project to develop and demonstrate a prototype tool to support Phasor Data Validation and Conditioning in real-time (DE-AC02-05CH11231).

As part of Phase 3, this Report documents the experience in surveying the industry and development and testing of the DV&C prototype.

## Table of Contents

Acknowledgement .....	i
Disclaimer.....	i
Preface .....	ii
List of Figures .....	iv
1. Introduction .....	1
2. Overview and Executive Summary .....	1
3. Phase 1 observations .....	3
3.1 Review of existing systems .....	3
3.2 Infrastructure recommendations .....	4
3.3 Development of the prototype .....	6
4. Phase 2 observations .....	7
4.1 Development of the error simulation utility.....	7
4.2 Demonstrations of the prototype.....	8
5. Summary .....	9

## List of Figures

Figure 1. Overall algorithm process .....	2
Figure 2. Structure of Data Validation Application .....	7
Figure 3. Phasor data error simulation utility .....	8

# Synchro-Phasor Data Validation and Conditioning Project

## Phase 3, Task 1

### 1. Introduction

The Synchrophasor Data Conditioning and Validation Project sponsored by the US department of Energy Consortium for Electric Reliability Technology Solutions (CERTS) program was started in December 2012. The project objectives are to develop, prototype, and test various methods for conditioning and validating real-time synchrophasor data. The project is divided into three phases.

- Phase 1: Conceptual Design and Prototype Development
- Phase 2: Prototype Demonstration
- Phase 3: Functional Specifications of the Data Validation System

In Phase 1 Electric Power Group, LLC (EPG) completed the design and prototype development to meet the data validation and conditioning requirements. These requirements have been developed by EPG based on surveys, literature research, and experience in working with customers.

In Phase 2 EPG developed an Error Simulation Utility that is capable injecting errors of various types into a synchrophasor data stream played from a file of synchrophasor data. This simulation utility was used to demonstrate the Data Validation and Conditioning Prototype using a stream of real synchrophasor data captured from an on-line system.

Phase three of this project has 3 tasks:

- Task 1: Summary Report of Lessons Learned in all three tasks
- Task 2: Functional specification for the Data Validation and Conditioning Prototype
- Task 3: Review Meeting with Project Participants

This report is Phase 3 Task 1, a report of lessons learned in the course of the first two phases. This will be presented in chronological order, the same as the tasks were worked on and completed.

### 2. Overview and Executive Summary

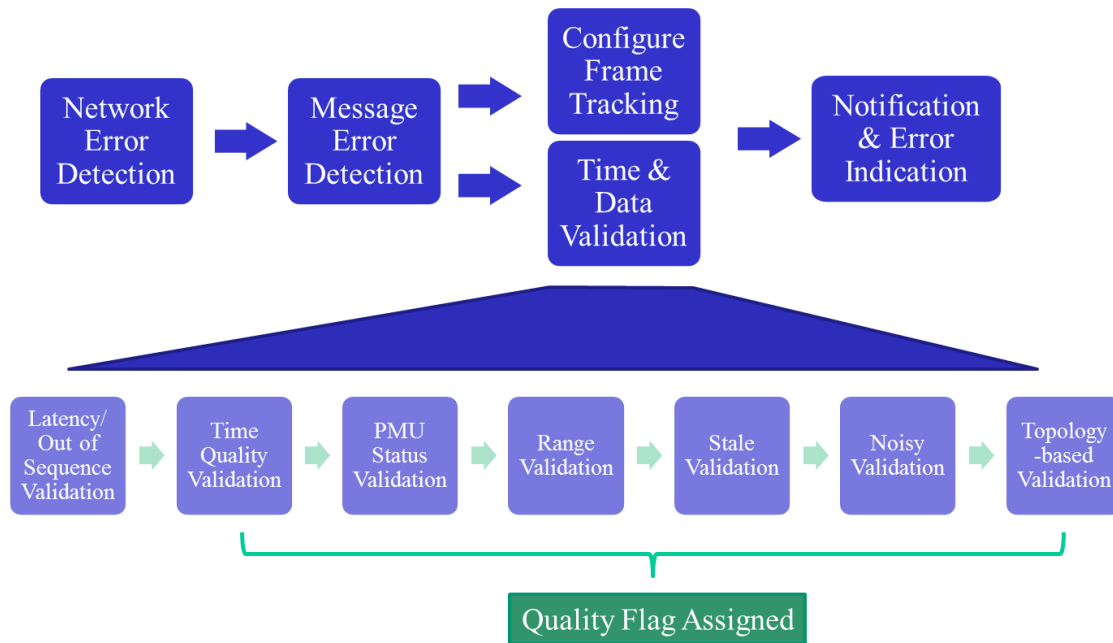
This report summarizes EPG experiences during this project, particularly the “lessons learned” as requested by the sponsors. In Section 3 we cover observations made during Phase 1 and in Section 4 we cover Phase 2.

The first task of Phase 1 was to review existing systems. This included both a literature review and survey of current projects. There was little published documentation on projects, so the review depended mostly on the survey. We surveyed 20 projects that provided a good cross section of current

development. Generally the approaches seemed to be successful and met the goals. The projects were not far enough along to assess the operation and maintenance approaches. The main weaknesses were data validation, system monitoring, and application deployment.

The second task in Phase 1 was to compile a best practices document. Since the information from the first task was not very comprehensive, EPG experience with many utilities was also used to complete the report. The report covers recommendations for project and system management, design and implementation, and operation and maintenance.

The third task of Phase 1 was to create the actual data validation and conditioning prototype (PDVC). EPG decided to focus on data centric methods rather than bring in a system model. EPG created algorithms based on errors that could be detected at each of 6 stages of processing. Also included was a way to tie these algorithms together and create a data quality flag as shown in Figure 1. This was coded as a service; configuration was provided through a GUI. The PDVC at this stage was demonstrated to project sponsors using artificially created data.



**Figure 1. Overall algorithm process**

Phase 2 focused on proving and demonstrating this PDVC utility. The first task of Phase 2 was implementation of an error simulation utility. Since most errors occur rarely, a simulator that could create errors on demand is essential. This simulator can use both artificial phasor data and data captured from a real operational measurement system. The second task of Phase 2 was to demonstrate the PDVC using actual phasor data provided from two utilities. Due to security considerations, we could not connect the PDVC to a real time data stream, so we received a data capture one utility. This data was run through the simulator and into the PDVC. Using the simulator to inject errors as we wanted, we demonstrated the ability of the PDVC to detect them. This demonstration was done for several

audiences. We were not able to obtain a set of real data from the second utility for demonstration due to some staffing changes. Both the PDVC and error simulation utility have been posted for project sponsor and participant download.

### 3. Phase 1 observations

#### 3.1 Review of existing systems

The first phase of this project was to review existing phasor measurement systems with an emphasis on those that were part of the Smart Grid Investment Grant (SGIG) projects. The object of the review was to determine user approach and experience with these systems. We planned to look at both the implementation phase and the operation phase of each project. For both phases we hoped to determine the management and technical aspects. Implementation management includes the scope of involvement, team composition, and progress monitoring. The technical aspects of implementation include scoping, design, materials selection, installation, and testing. Operation management includes team selection and guidance, maintenance oversight, change management, and replacement planning. Operation technical aspects include troubleshooting and repair, maintenance, and modification. Aside from the phasor system itself, we hoped to survey the data use aspects including experience with present and planned applications.

The review included both a literature search and a review of projects directly with utilities that had projects. The literature search did not turn up much information; most of the papers, reports, and presentations were proposed projects rather than facts and experiences. That did provide some overview and indicated companies that had active projects.

The project team drew up a list of all the utilities in North America with involvement in phasor system projects. There were over 100 on the list, far more than could be reasonably interviewed. We narrowed it to a list that included the larger and the more complete projects, making sure that we had a cross section of all types of projects including some that had produced interesting results. From that we contacted representatives of about 35 projects to ask for participation. Of those, we ended up with 20 participants. The others did not want to spend the time, did not feel they had information to contribute, and were unsure of what they could share (security concerns),

We decided that rather than just send a form, we would do live interviews. That allowed getting clarification of details that may be unclear in a filled in form. It also assured that we got a response, as mail in surveys tend to have a low response rate. Given the variety of states of the projects, it proved useful to be able to probe individual details. We created an interview form that we provided to the participants before the interview. This form helped to assure that we covered the same questions with each utility for comparability and the interviewees were prepared for the questions.

Generally we found that most projects were not far enough along to have operational experience. They were predominately in an implementation phase and in many cases, not complete enough to draw conclusions about how successful the approaches were. Still, we were able to determine that the

management and implementation approaches were rather similar across all projects. The main points were:

- Project administration generally followed company procedures for like projects for substation and control center equipment. There were some extra coordination problems due to the fact that field and control center need to be tightly coupled with communications, and coordination outside an individual utility.
- The architecture of most projects followed a typical pattern: PMU to TO-PDC to ISO-PDC with various applications at each control center. In most cases data archiving was added at both TO and ISO control centers.
- On-line data validation was generally not performed; automatic notification of problems was not common.
- Operation success and data reliability were reported as good to excellent, though reports at NASPI and other meetings seem to indicate otherwise.
- Most utilities had interest in expanding their systems and deploying more applications. However these extensions depend on future funding and there was no clear idea of what applications would be deployed or what they would do.

Overall we gathered interesting and useful information that created a basis for this project. Companies handled these projects much like they would do any other project that involved the same kinds of equipment. They adapted to the special requirements of phasor systems successfully. They were not far enough along to provide insights on the operation and use of these systems. Our experience in conducting these review provided the following insights:

- Interviews take a lot of time. We had several people on the interviewing group and each tended to hear different things, so drawing up the response in writing was time consuming also.
- The script has to be carefully designed to get consistent answers. We had to rework the script after the first 2 interviews to apply it more consistently.
- With an interview, we could skip over aspects that were less important with a particular utility and go into more detail with important parts. While the results were more complete, they were also more difficult to correlate with other results. Deviation from the script made a statistical approach to evaluation impossible.
- There was little concern or planning for data quality, probably because the implementations were not complete.
- Utility plans for systems use that use synchrophasor data varied widely, so there was little common ground to focus on applications. Several of the smaller utilities were participating at their ISO request and had no plans for data utilization. Several did not know what they could do with it.

### 3.2 Infrastructure recommendations

The EPG team planned to use the results from the survey, both of literature and directly from utilities, for drafting a “best practices” document. Because projects were not far along, there were not a lot

conclusive results of the implementation phase and nearly nothing on operation and maintenance. Fortunately EPG has had considerable involvement with synchrophasor projects through long time participation in the industry. Some members also had experience with these systems through prior employment. The “best practices” document was prepared using the survey basis and supplemented with EPG experiences.

The report is divided into three main sections. The first is administration. This is followed by implementation and finally operation and maintenance. The key administration point is multidisciplinary team is needed since these systems cover both substation and control center equipment with the communication to tightly couple them together. Installation, operation, and problem resolution require cooperative work of all three areas. This starts at the system conception stage and continues through O&M. Documentation and change management is part of this.

The implementation phase needs technical leaders from all the disciplinary areas. Applications for these measurements are usually brought in as an afterthought; they should be considered first to help guide the location and characteristics of the measurement. This assures the right equipment will be chosen as well as communication and control center hardware to match. Once installed, the measurements need to be validated. This should include both comparison local substation or portable instrumentation and comparison with other reporting systems, particularly SCADA.

Operational systems should include tools for monitoring performance and problems. Effective maintenance requires prompt attention to problems, both those that cause failure of data as well as those that simply degrade accuracy. A routine maintenance program should include enough measurement validation to locate and correct degradation that is not otherwise noticed. Troubleshooting procedures need to include contacts in other organizations as these systems span several disciplines and sometimes several companies.

The EPG team found it is difficult to make one complete set of simple recommendations that everyone can use because:

- Utilities of different size and scope have different needs.
- There are a lot of infrastructure issues that the utility has to live with, such as pre-existing communication facilities, certain lines that can be accessed for measurement, etc.
- Development schedules tend to be fixed by external forces that cannot easily be changed.
- Regulations like NERC CIP create uncertainty and can change and require the utilities do things differently.

Consequently the recommendations are rather general. Utilities need to develop their own procedures based on their particular circumstances, and be willing to alter them when the situation changes. There were some common themes that we noted, including:

- Validation of signals is difficult when measurements travel through several different companies.

- Validation of measurements has become a big issue but utilities are not comfortable that they know what to do.
- Users are still struggling to find the proper niche for these measurements
- There is no “killer app” that will make phasor measurements essential.

The best practices document includes two long annexes. The first provides guidance on validating measurements both in the substation and at control centers. The second details troubleshooting for common and a few unusual types of problems.

### 3.3 Development of the prototype

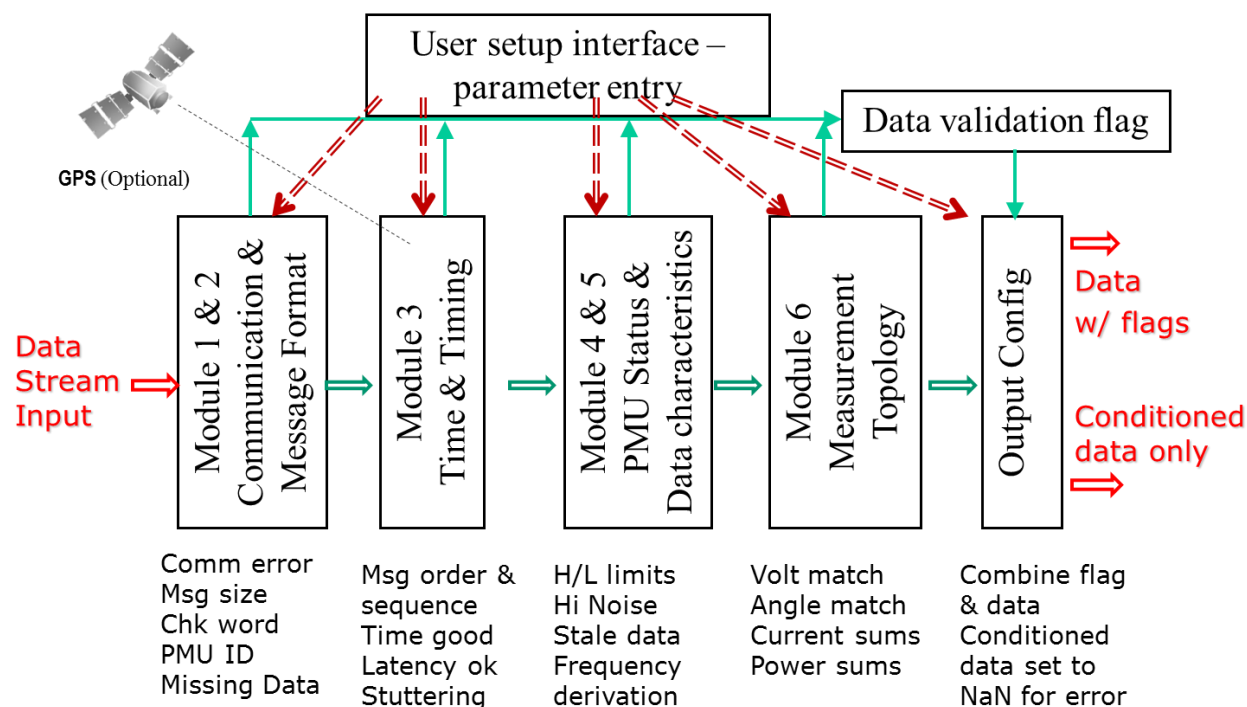
EPG spent the first 8 months of the project reviewing existing projects and making the best practice recommendations. By the time this prototype development was started, Virginia Tech had presented their approach for data validation. This included using a linear state estimator and a 2<sup>nd</sup> order prediction method to look at individual signals. Rather than attempt to duplicate their work, EPG decided to focus on data-centric methods. The approach is simply to examine the data in every way possible for the effects of errors. When they are discovered, the data will either be declared bad and set to an invalid state or flagged to indicate it is questionable if it cannot be declared bad.

The first stage of development was to look at every type of error that has been identified and catalog the effects that will be seen in the data. The next stage is to create an algorithm that will detect the effect in the data and differentiate it from true system data. The last stage is to code the algorithm.

EPG created 6 algorithms to cover the types of errors by the stage of identification. These are:

1. Module 1- Communication Interface: This module is designed to check for errors that may be introduced in the communications chain such as dropped bits, incorrect message frames, and CRC errors.
2. Module 2 – Message Characteristics: This module checks for message format errors such as length, destination address, type identification, and CRC16-check.
3. Module 3 – Timestamp: This module checks time tags for sequencing, data rates and transmission delays.
4. Module 4 – Quality Flags: This module utilizes all the flags available in the C37.118 standard to distinguish between good, bad, and uncertain measurements. Bad data is converted to NaN, suspect data is flagged, and all data is passed on to the next module for further processing.
5. Module 5 – Data Characteristics and Self-Checking: This module incorporates algorithms to check for unreasonably high or low values of voltage, current and frequency, data that is stale (not refreshing), and excessively noisy. Depending on severity, data that fails testing is declared bad and set to NaN or uncertain and flagged.
6. Module 6 – Topology Checking: The last module uses system topology to build algorithmic logic checking. For example, the sum of currents into a bus should be 0, and voltages at the same bus should be the same.

The modules are linked together into the data validation application as shown in Figure 2. Each one treats the data at an appropriate stage, such as the communication error detection at the communication interface stage. A data quality flag is assigned to each data item at the first stage and carried with the data. The data quality flags from the PMU apply to the whole data frame, but these flags apply to each data item. As soon as the phasor data extracted from the message, it is converted into floating point to simplify handling, preserve resolution, and flag bad data.



**Figure 2. Structure of Data Validation Application**

After coding and linking the modules together, we tested them with samples of good data and then data with errors of the type that the algorithm was designed to detect. After the usual bug detection and fixes, the algorithm was ready for demonstration and evaluation, followed by improvements if some were identified.

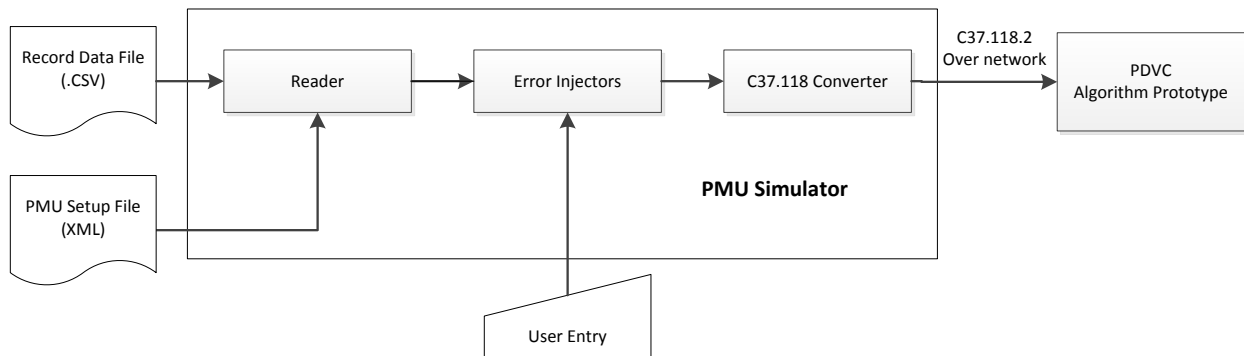
EPG has a lot of experience with project development of this type. It also has put together a lot of presentations to introduce technical subjects like this to utility users. Here the implementation and presentations went smoothly, so there are no particular difficulties to report.

## 4. Phase 2 observations

### 4.1 Development of the error simulation utility

Creation of a testing utility was conceived as the most expedient way to test the validation prototype. In EPG experience, the most common error in synchrophasor systems is data dropout. This is easy to

simulate but does not tell anything about the other kinds of errors that can occur. Most of the other errors occur rarely and in special circumstances. It is nearly impossible to capture data streams with each one of these errors in it to use for test. An error simulator where we could inject a specific error at a specific time and check detection is the best way to perform this testing. Figure 3 illustrates the simulator data flow.



**Figure 3. Phasor data error simulation utility**

The testing utility was initially conceived as a flow-through tool that would take apart an existing stream, create user errors as needed and then sent the stream on. Two problems with this approach emerged: first, creation a utility with the required speed and flexibility was very challenging; second, EPG did not have a real-time stream to work with. Requiring a real-time stream also limits the cases where such a utility could be used in future testing. After careful consideration, EPG developed a utility, called “PMUsim”, so it could work with files of data saved in CSV format. This allows using data captured from real-time data streams as well as creation of artificial data with a simulator or other program. PMUsim takes the captured data and applies a time stamp from the host computer, so the data appears to be real-time and is up-to-date with other live applications.

PMUsim worked out well. The configuration is a little challenging because there are so many options. PMUsim allowed doing demonstrations by WebX as well as in meetings. No connections to data external sources are required. Other than explaining the complexity of configuration and the setting definitions, there have been no issues with the simulator.

## 4.2 Demonstrations of the prototype

The project plan specified demonstration of the validation and conditioning prototype with real data from two power utility companies. Due to security considerations, the utilities decided to supply a data capture for demonstration rather than arranging for connection directly to the utility data streams. EPG secured a data capture from one of the utilities in May 2014. EPG formatted the captured data so it could be fed out through PMUsim to the Phasor Data Validation and Conditioning prototype (PDVC) to fully demonstrate its error detection capability.

A full demonstration by WebX of the PMUsim and the PDVC was made in June. Project sponsors and utility participants were invited. Webinar participants were satisfied with the demonstration; no

comments on the performance were received. EPG did receive requests to obtain PMU<sub>sim</sub> and PDVC. These were posted for download in July and are available to all US Utilities and Labs.

EPG was not able to obtain data or provide a demonstration to the second designated utility company due to some administrative changes there. However EPG received authorization from the first utility to continue using the data they provided to do demonstrations. Using that data, EPG has demonstrated the PDVC using PMU<sub>sim</sub> at a number of utilities including PJM, Duke, AEP, LCRA, and SRP as well as for WECC and at a JSIS meeting.

One challenge using the PMU<sub>sim</sub> and PDVC is that they allow making settings at very low levels for data error injection and error detection respectively. With large data sets (such as the one supplied for test), setting up detailed error detection is tedious. For example, with the 8 kinds of errors the PDVC will detect for each measurement, a modestly sized data set with 200 measurements (40 PMUs with 5 phasors each) requires 1600 settings. Anticipating this problem, the PDVC can apply settings from one measurement to all other measurements of the same type. So one basic default for all measurements of a type can be entered and then only those that need special settings can be modified.

Another challenge is understanding the measurement impairment parameters and how to make the settings. For example, what does high noise look like and how do the settings work. The functional specification will address this issue by defining all the terms and the settings used in the PDVC.

## 5. Summary

EPG studied the issue of validating synchrophasor data and investigated ways to condition the data for applications that use the data. The first phase of the project was started with a survey of synchrophasor measurement systems. This included both direct assessment of utility projects and review of published literature. EPG subsequently produced a best practices document based on their experience with synchrophasor systems and information from the survey.

The survey and insight from drawing together the best practices document provided background for development of the prototype Phasor Data Validation and Conditioning (PDVC) utility that would meet the needs of synchrophasor data system users. This prototype was first tested with artificial data to prove that it could detect errors of each type specified in contract as well as others that EPG has encountered in its extensive work with these data systems. For more comprehensive testing, an error simulation utility was developed. This simulator can use artificial or recorded real data and can create specific errors at a specific time in a data stream. Further comprehensive tests with the simulator using data from an operational phasor system validated the PDVC capability and operation. The operation was also demonstrated to project sponsors and several utilities.

Feedback from evaluators has been incorporated into improving this product. Both the Error simulator and the PDVC have been made available to all US Utilities and research labs, who are party to this work. This report summarizes experience and 'lessons learned' through this project. It is hoped researchers

and developers of synchrophasor projects will find this useful. EPG appreciates the support and commentary that have been provided in the course of this work.